LCA Case Studies

Life Cycle Impact Assessment of the Average Passenger Vehicle in the Netherlands

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Abstract

Goal, Scope and Background. In this article, the Life Cycle Impact Assessment of the average passenger vehicle of the Netherlands is performed, with emphasis on the current dismantling and recycling practice in this country. From calculations on recovery rates of the several material streams from ELV (End-of-Live Vehicle) recycling, it seems that attaining the European ELV legislation recycling targets (Directive 2000/53/EC 2000) is very difficult, even for countries with advanced collection and recycling infrastructures such as the Netherlands. An LCA of the current average passenger vehicle of the Netherlands, including a detailed modelling of the recovery and recycling should form a sound basis for comparison with alternative automotive life cycle designs and legislation efforts.

Model and System Definition. An average passenger vehicle is defined, having average weight and material composition. A cradle to grave approach is taken, including all relevant upstream processes for the production of materials and fuels, and the return of the recycled materials to the material cycles in the EOL (End-of-Life) phase. A particularity of this model is the detailed description of the Dutch collection and recycling infrastructure, with current data for the shredding, separation and metallurgical recycling processes (ARN 2000, Barkhof 1998, Chapman 1983, Püchert et al.1994, Worrel et al. 1992).

Results and Discussion. According to the Eco-indicator 99 (EI99) (Ministerie van V.R.O.M 1999), the largest environmental impact of the passenger vehicle's life cycle occurs in the use phase - over 90% -, due to the combustion and depletion of fossil fuels. This is in agreement of previous studies (Kasai 2000, Kanesaki 2000). Also in the other life cycle phases, the use of fossil fuels is the dominant impact, even for the production phase. Resource depletion due to the use of the materials employed in the vehicle causes a comparatively lower environmental impact, namely due to the high recovery rate and efficiency of the metallurgical recycling, that balances for about 30% the total impacts of the materials production and use. NO_x emission was one of the smallest emissions to air in quantity, but was responsible for 36% of the impact of the life cycle, while CO_2 was the largest emission to air but caused only 6% of the environmental impact.

Conclusion and Recommendation. Although there is a growing awareness and concern on increasing the recyclability of vehicles, the use phase still has the largest environmental impact of the vehicle's life cycle. A life cycle assessment can be a sound basis to evaluate and compare design alternatives to increase the sustainability of passenger vehicles. The ASR (Automotive shredder residue) is currently the greatest concern with regard to the recovery targets. It is a large amount of materials (about 32 wt.%), difficult and costly to recycle, and thermal recovery is limited to a maximum of 15wt.% in 1015 by the European ELV legislation. Joint efforts from the automotive industry and legislative institutions are required to find a sensible solution. LCA can be a useful tool to support legislative decisions, as purely weight-based recovery definitions are not adequate to evaluate the sustainability of the automobile life cycle.

Keywords: Eco-indicator; emissions; environmental impact; end-of-life (EOL); end-of-live vehicle (ELV); LCA; life cycle impact assessment (LCIA); recycling; resources; passenger vehicles

1 Goal, Scope and Background

1.1 Background

Every year, many passenger vehicles reach the end of their useful lives, of which about 300.000 in the Netherlands, and need to be disposed of in a sensible manner. They contain valuable materials that need to be recovered. Additionally, landfill space is scarce and costly in this country. The European ELV recycling directive demands a recovery of 85 wt.% for the year 2006, rising to 95wt.% in 2015 (Directive 2000/53/EC 2000).

On the other hand, it is known that the use phase of a vehicle is responsible for the largest share of the environmental impact of its life cycle (Castro et al. 2001, Kanesaki 2000, Kasai 2000). Therefore, the automotive industry has been making efforts to reduce vehicle weight as a way to reduce fuel consumption and hence emissions. The use of lightweight materials can contribute to a significant weight reduction as they replace traditionally used heavier materials such as various ferrous alloys (Automotive engineering International (1) 2000). There is a tendency to use more polymers, aluminium, magnesium and various composite materials. Other attempts to reduce vehicle weight consider the use of newly developed ultra-strong steel alloys in a different body design, as is the case of the ULSAB (Automotive engineering International (2) 2000) (see **Fig. 1**).

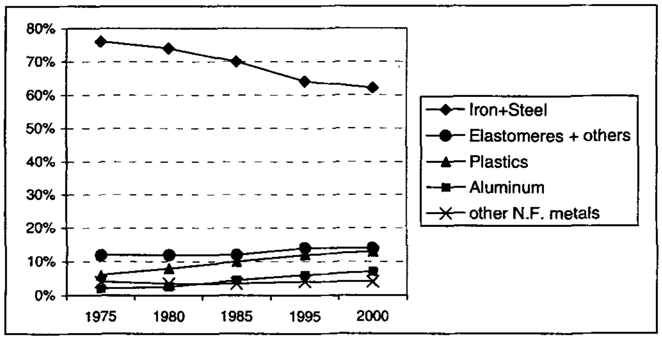

Fig. 1: Material composition trends of the average European passenger vehicle (Püchert et al 1994)

Lightweight metals are recyclable and have relatively high prices in the scrap markets, but other lightweight materials such as polymers and composites represent a challenge for the recycling industry. Their recycling is economically unattractive, as a satisfactory recycling technology is not developed yet (Tempelman 1999). When a mix of all these materials is present in the ELV, recycling becomes even more complex and costly, due to high contamination of the recovered materials and as a result, a large amount of material goes to landfill. Currently, weight reduction and increase of the recycling rate are conflicting requirements for the automotive industry.

The recycling rate targets imposed by the ELV legislation for 2006 can be expressed by the following equation, adapted from (Aboussouan et al. 2003):

$$\alpha \cdot P + \beta \cdot M \geq 0.85 \qquad (1)$$

where P stands for the non-metallic fraction of the ELV and M for the metallic fraction. The coefficients α and β represent the recovery rates of the two fractions over the entire recycling chain, from dismantling/shredding to secondary materials production.

If a collection rate of 100% is assumed, for simplicity of the calculations, the recovery coefficient for non-metals, α, has typically a low value for ELV recycling, and β is high, typically over 0.9. **Fig. 2** shows the recovery rates obtained, as a function of the non-metal content in the ELV. For the calculations $\alpha = 0.15$ and $\beta = 0.95$ were used. The ELV of the year 1998, containing about 23% non-metals, according to the values of Tables 2 and 3 and Fig. 3, and the ELV of 2015, containing about 32% weight of non-metals, are shown in Fig. 2 as well. It seems obvious that the recovery coefficient of the non-metal fraction α will have to increase tremendously, to values similar to those of the metals recovery coefficient, so that the recovery of ELVs can reach the legislated target values. This is hard to achieve, particularly if the trend of increasing the non-metal content in the automobile continues, as the two ELVs in Fig. 2 indicate. This poses a tremendous challenge to the automotive industry, as the imposed targets are impossible to attain. Maintaining the current weight reduction trends without a drastic increase in the recovery of non-metals means that the automotive industry and consumers are facing an increasing recovery problem. Either the recovery technology must improve or the design must be changed. Recycling technologies for non-metals seem to be facing various difficulties in the practical implementation (high levels of contamination are a serious limitations to the recycling of those recovered streams) and it seems thus that a reasonable solution for the near future must be found in the design and material composition of vehicles, and in alternatives to the mechanical recycling of ASR.

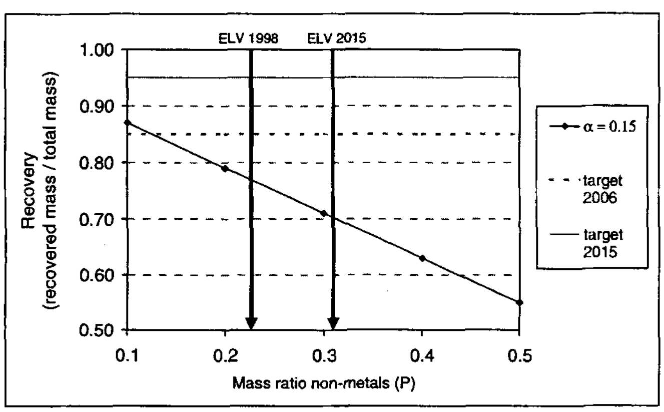

Fig. 2: Recycling rates of the ELV as a function of recovery percentage of the non metals and non-metal content

The present study aims to determine the environmental impact of an average passenger vehicle in the Netherlands as a basis for comparison with other vehicle design and construction alternatives to be generated. The Eco-Indicator 99 method was used for the evaluation of the environmental impact (Ministerie van V.R.O.M. 1999). This method calculates the overall impact of the inputs and outputs of the considered subject. Typical of this method is that it calculates the benefits of recycling by subtracting prevented impacts by the recycling of materials.

1.2 Goal and scope

The life cycle impact assessment aims at completing the data existing for the LCI (Life Cycle Inventory) of passenger vehicles at the Delft University of Technology. It also aims at calculating the environmental impact of an average passenger vehicle in the Netherlands, using the results as a basis for comparison with other automotive design alternatives. A better understanding of the environmental impact of the passenger vehicle may be beneficial for the development of more sustainable vehicles with lower environmental impact and a more efficient resource use. To analyse in detail the effects of materials recovery in the EOL phase, a detailed multi-level EOL scenario was developed, describing the current situation in the Netherlands.

2 System Definition

2.1 Functional unit

As a base for comparison, an average ELV, with average weight and composition is defined. The vehicle weight and material composition corresponds to the Dutch situation, the empty weight is considered to be around 900 kg. This data concerns an ELV discarded in 1998, i.e. a vehicle that was produced typically around 1984. As use phase, the average distance cov-

ered by a vehicle in the Netherlands during its lifetime, approximately 14 years, was used: 200000 km (ARN 2000). The fuel used in this study was the most commonly used in the Netherlands, unleaded gasoline, with an average vehicle consumption of 11.5km/l (Delft University of Technology 2000).

2.2 System boundaries

A cradle to grave approach (Ministerie van V.R.O.M. 1999) of the passenger vehicle was made, considering:

- Production, including materials production and transport, components and fluids production and vehicle manufacturing;
- Use of the vehicle, including production and transport of the fuel and driving over the distance mentioned above;
- Maintenance operations, namely the change of oil and the replacement of tires and battery;
- End-of-life processes, including a detailed description of dismantling, shredding, materials separation, transport, recycling of the materials and landfill of the rest fraction.

All important upstream processes and required materials are also included, as is common in LCA studies. The Idemat 2000 database (Delft University of Technology 2000) was used as data source of the study, being complemented by publications when necessary (Barkhof 1998, Chapman 1983, Püchert et al.1994, Worrel et al. 1992). The Simapro software version 4 was used for the calculations (Pré Consultants 2000). Fig. 3 gives a simplified overview of the unit processes involved, with emphasis on the EOL processing.

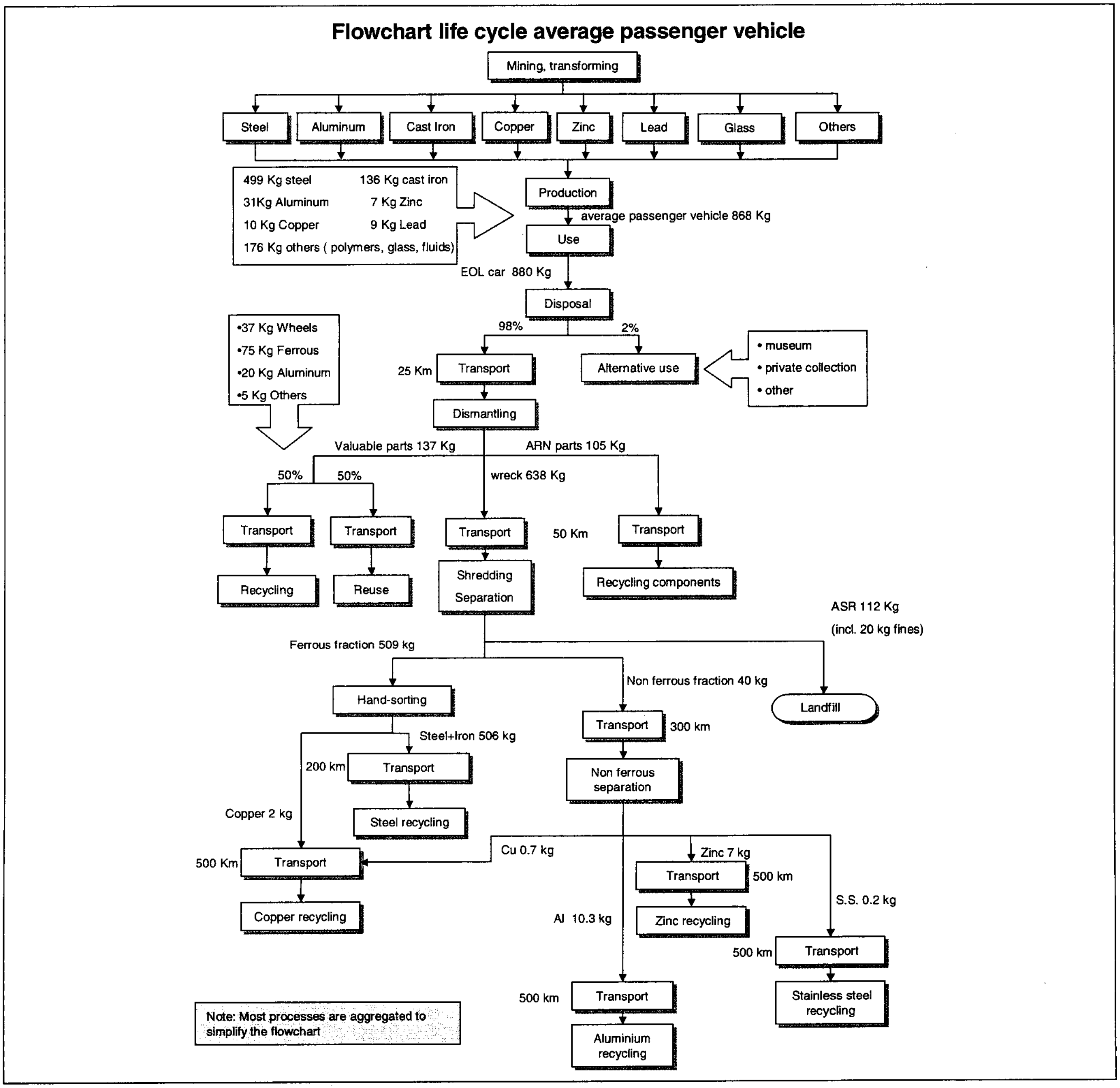

Fig. 3: Simplified flowchart of the life cycle of an average passenger vehicle for the Netherlands, with emphasis on disposal and recycling

3 Modelling the Average Passenger Vehicle

3.1 Mass balance

The average passenger vehicle for the Netherlands is defined as a passenger vehicle with average composition and weight. To determine the average weight and material composition, 700 ELVs were selected to form a representative sample of passenger vehicles for the Netherlands (Barkhof 1998). They were processed simulating what happens in reality. A number of parts were removed for re-use (e.g. doors) or sold separately for recycling because of its value as replacement part or material content (e.g. engine parts, gear box, light alloy wheels). The dismantled wrecks were then shredded and the mass and composition of the resulting streams was determined.

Because the authors found no statistical data regarding the dismantled parts, the mass values of the ELVs were estimated by comparison with those present in the literature for a newly produced vehicle of the correspondent production period (Püchert et al. 1994). **Table 1** summarises the values obtained. **Table 2**

Table 1: Average ELV composition (1998)

Component / material	Mass (kg)
Shredded wreck:	**638**
• Ferrous	506
• Aluminium	10
• Other non-ferrous	10
• Automotive Shredder residue	92
• Dust and rust	20
ARN dismantled parts	**105**
Metallic dismantled parts (e.g. engine, wheels):	**137**
• Ferrous metals	75
• Aluminium	20
• Other non-ferrous (Cu)	5
Total ELV	**880**

Table 2: Dismantled parts and respective average weight, according to ARN

Part	Average weight (kg)
Cooling liquid	3.6
Oil	4.9
Brake oil	0.3
Battery	13.3
Glass incl. Front lights	25.4
Tyres	27.9
Air chamber (inner tyre)	0.2
PUR-foam	6.5
Rubber strips	7.7
Plastic bumpers	5.5
Safety belts	0.35
Coconut fibre	0.7
Windscreen liquid	0.9
LPG-tanks	0.06
Grilles	0.8
Back lights /direction lights	1.4
Wheel covers	0.7
fuel	5.0
Total	**105.21**

shows a complete list of the ARN[1] components that are currently dismantled before the ELV is shredded (ARN 2000).

3.2 Life cycle breakdown

It was not intended to make a detailed description of all the vehicle components. The description is rather focused on materials and the related processes. Due to the large number of components constituting the average passenger vehicle and its statistic nature, the materials were included in this study grouped in families. The modelled vehicle was divided into several systems/components, according to the several EOL (end-of-life) processes it undergoes (see Fig. 3).

3.2.1 Manufacturing

Materials and processes required for the production of each system/component were included, the metal processing routes being the most important, due to the relatively high amounts of required energy and emissions produced. The data used was obtained from the IDEMAT2000 database (Delft University of Technology 2000) and from metallurgy literature (Chapman et al. 1983 and Worrel et al. 1992). The European average production processes and energy consumption were adopted.

3.2.2 Use phase

For the use phase, it was considered the transport of 1.54 passengers and respective luggage over 200.000 km, with a consumption of unleaded gasoline of 11.5 km/L. The production and transport of gasoline was also included.

As maintenance, the replacement of tires, battery and oil was included. The average passenger vehicle is estimated to require 13 tires, 3 batteries and 13 oil changes during its lifetime.

3.2.3 End-of Life

The EOL scenario adopted was the Dutch scenario. A comprehensive description of the Dutch collection and recycling infrastructure was made, with detailed current data for the shredding, separation and metallurgical recycling processes required to bring the materials back into the industrial production systems (ARN 2000, Barkhof 1998, Chapman 1983, Püchert et al. 1994, Worrel et al. 1992).

The ELV is collected and many parts are dismantled as described in 3.1. These parts are reused or follow dedicated recycling routes (e.g. battery). The remaining wreck is shredded and the material streams separated. Most of the metals are recovered (about 99%) and further metallurgically processed into secondary alloys. The recycling rate varies per metal according to the typical processing losses. The remain-

[1] ARN, 'Autorecycling Nederland', is the organization responsible for the ELV management in the Netherlands. A list of these parts is presented in Table 2.

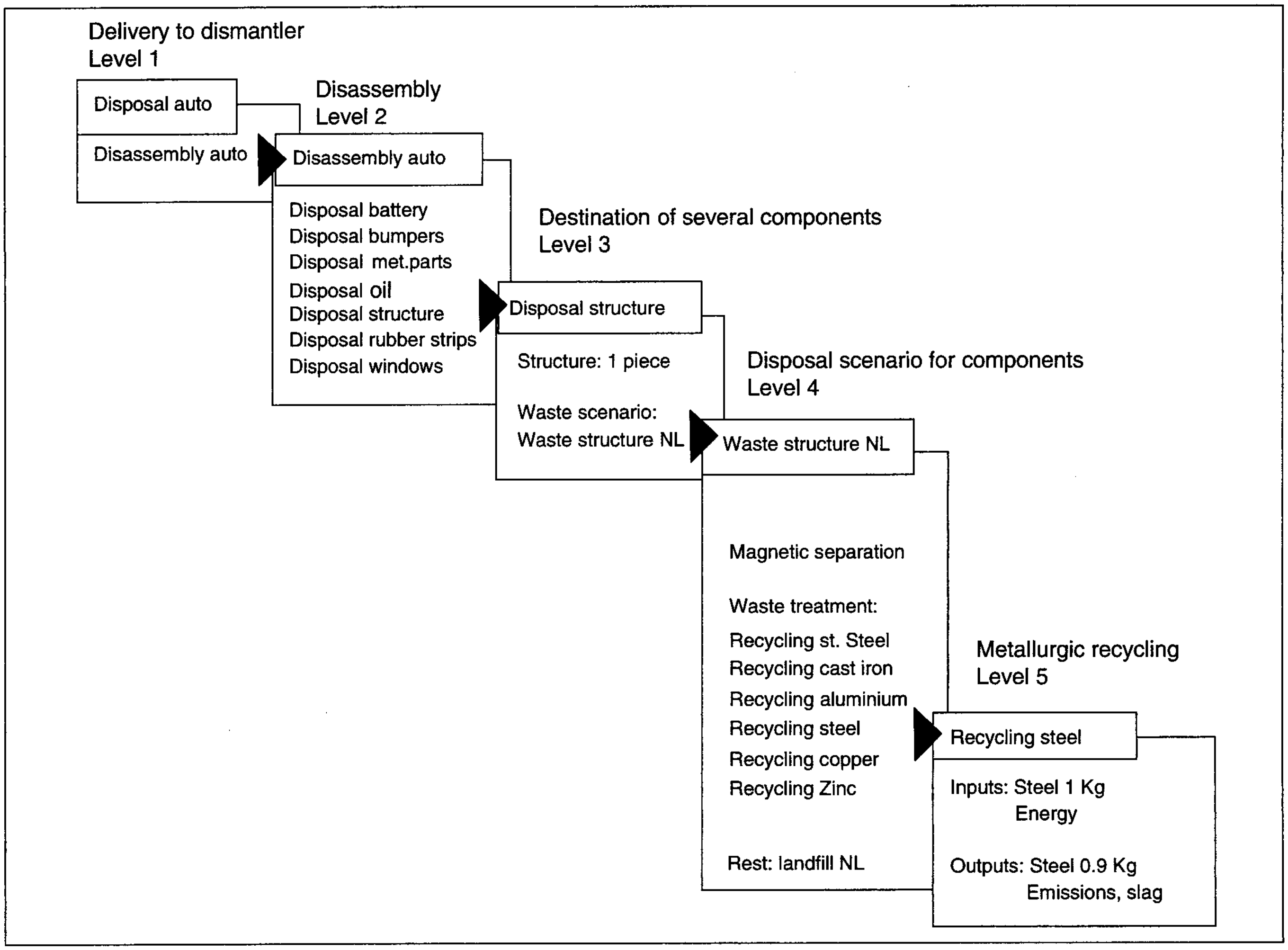

Fig. 4: Scheme of implementation of EOL scenario, with its nested levels

ing mix of materials, called ASR (Automotive Shredder Residue), constituted mainly by polymers, glass and fine particles, is landfilled. **Fig. 4** schematises the implementation of the EOL scenario for the LCA.

4 Results and Discussion

The Eco-indicator 99 considers 11 impact categories, shown in **Table 3**, in the areas 'Human Health', 'Ecosystem Quality' and 'Resources'. To obtain an eco-indicator value, all impacts in the several impact categories need to be combined and gathered into a single value. When using the Eco-indicator 99, it is possible to choose between three perspectives, the 'egalitarian' (E), the 'individualist' (I) and the 'hierarchic'(H). The different perspectives attribute different weights to the several impact categories. More information can be found in (Ministerie van V.R.O.M 1999). The scientific community accepts generally the hierarchic perspective as a moderate position, and therefore that was the perspective adopted in this study. Because fossil fuels combustion and depletion has such a dominant effect, the difference in weighting will not produce significant changes in the eco-indicator results. Further, the effect of using different eco-indicators was investigated previously and the results were also consistent among all indicators, with minor differences that can be attributed to intrinsic differences in the calculation of the environmental impacts that characterise the eco-indicators such as the absence or not of certain impact categories, e.g. 'resources' and 'land use' (Castro et al. 2001).

Table 3: Impact categories covered by the eco-indicator EI 99

Areas (Unit)		Impact categories
Human Health (DALY)	1.	Carcinogenity
	2.	Respiratory Organic Substance
	3.	Respiratory Inorganic Substance
	4.	Climate change
	5.	Radiation
	6.	Ozone layer Depletion
Ecosystem Quality (PDF*m²y)	7.	Ecotoxicity
	8.	Acidification / Eutrophication
	9.	Land use
Resources (MJ surplus)	10.	Minerals
	11.	Fossil fuels

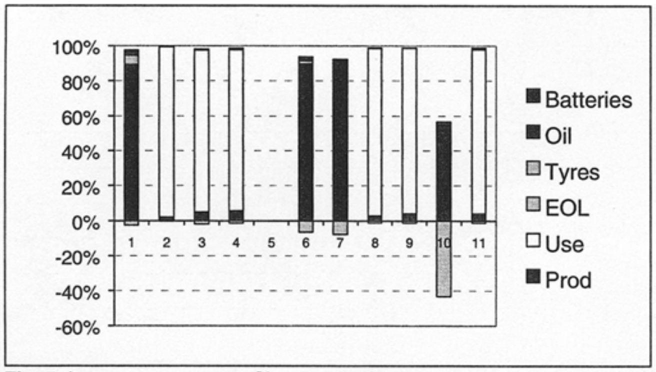

Fig. 5: Impact assessment: Characterisation

Table 4: EI99 values, corresponding to figure 4

Phase	EI99(Pt)
Prod.	264
Use	3930
EOL	–77.9
Tyres	22.5
Eng. oil	0.261
Batteries	8.41

4.1 Characterisation

The graph in **Fig.** 5 shows the results for the 'characterisation' step of the environmental impact assessment. The production phase is the most important in the categories 1, 6 and 7 discriminated in **Table** 3. The use phase has large contributions to most of the impact categories: 2, 3, 4, 8, 9 and 11. The largest contribution of the EOL phase is to category 10, 'Minerals'. The negative impact (downward column) means a benefit to environment, due to the recovery of the materials. 'Tyres' and 'Engine oil' have a very small impact, being the largest contribution in impact category 1.

4.2 Evaluation

The results for the evaluation are shown in **Fig.** 6 and **Tables** 4 and 5. As confirmed by earlier studies of other passenger vehicles (Kanesaki 2000 and Kasai 2000), the use phase is dominant, accounting for more than 90% of the environmental

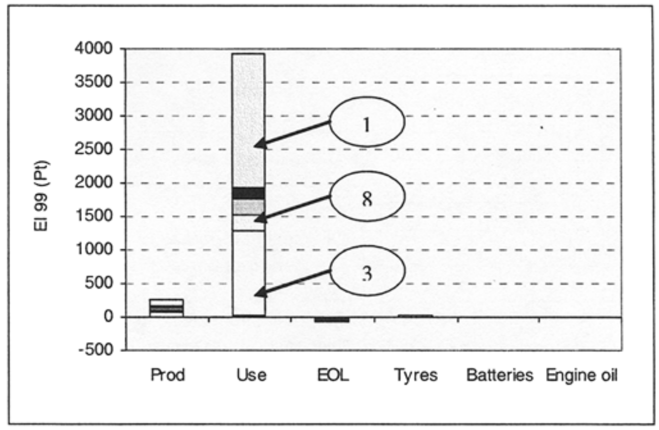

Fig. 6: Impact assessment: Evaluation

impact of the life cycle. The production phase and 'Tyres' life cycle have relatively small environmental impact (less than 1% of the total). The EOL phase shows a negligible burden and a small benefit. Though the benefit is small compared to the burden of production, it means that this phase compensates about 30% of the impact generated during the production. The largest contributors to the impact of the use phase are impact categories 3, 8 and 11. The sum of 3 and 11 together account for 83% of the impact of this phase. Category 11 is also the largest contributor to the other life cycle phases, although it is difficult to visualise in Fig. 6, due to the relatively very small values. This means that in each life cycle phase, the dominant impact is fossil fuels depletion, with exception for the EOL phase and batteries' life cycle, where the emission of respiratory inorganic substances slightly surpasses it.

4.3 Emission analysis

The **Tables** 6 and 7 show the major emissions to air and water respectively and their relative contribution to the environmental impact of the vehicle's life cycle. It can be seen from table 6 that most of the emissions are released in the use phase, and their contribution to the total eco-indicator value is not related only to the amount of the emission, but very strongly to its impact in the ecosystem and human health. NO_x is one of the smallest emissions in weight units,

Table 5: Percentage contribution of each impact class for the environmental impact of each life cycle phase

Impact category	Production (% EI 99)	Use (% EI 99)	EOL (% EI 99)	Tyres (% EI 99)	Engine oil (% EI 99)	Battery (% EI 99)
1	2.31	0.00	–0.22	1.57	0.01	2.38
2	0.11	0.35	–0.06	0.10	0.04	0.20
3	25.54	32.66	**–35.53**	14.00	6.35	**44.44**
4	5.56	6.04	–4.55	7.17	0.95	7.81
5	0.00	0.00	0.00	0.00	0.00	0.00
6	0.01	0.00	0.00	0.00	0.00	0.00
7	23.35	0.00	–6.61	2.12	0.01	1.25
8	2.78	6.15	–3.64	2.16	1.07	4.35
9	2.67	4.06	–2.46	1.49	33.94	0.46
10	4.98	0.00	–13.36	0.05	0.00	5.32
11	**32.69**	**50.74**	–33.56	**71.34**	**57.62**	33.79
Total	**100**	**100**	**–100**	**100**	**100**	**100**

Table 6: Largest emissions to air in the use phase compared to the same emissions for the entire life cycle and contribution to total environmental impact according to EI 99

Substance	Emissions Life Cycle (kg) (1)	Emissions Use Phase (kg) (2)	(2) / (1) (%)	Contribution to EI (%)
NO_x	546	538	98.5	36.2
CO_2	4.57E+04	4.34E+04	95.0	6.0
Zn	0.00	0.23	0.0	1.3
SO_2	26.40	19.40	73.5	1.0
Dust	5.60	3.73	66.5	0.4
CxHy	421.70	414.45	98.3	0.3

Table 7: Largest emissions to water and contribution to total environmental impact according to EI 99

Substance	Emissions Life Cycle (Pt)	Contribution to EI (%)
Ni	3.34	8.07 E-02
As	0.88	2.20 E-02
Cd	9.15 E-02	2.20 E-03
Cr	6.09 E-02	1.50 E-03
Cu	3.58 E-02	9.00 E-04
Zn	6.09 E-02	1.00 E-04

but has the highest eco-indicator value of all. The largest emissions during the other life cycle phases (Production and EOL) are SO_2 and Zn, which originate due to primary and secondary metal production and overseas transport. Table 7 shows the most important emissions to water. They are all heavy metals, but their contribution for the total environmental burden is very small.

4.4 Resource depletion

Another important issue in the vehicle's life cycle is the analysis of the resources lost, when aiming at a sustainable resource use. Table 8 shows the most significant contributions to the 'Resources' impact category. Two magnitudes can be seen in Table 8. The fossil fuels, above, with large contributions for the eco-indicator 99, and the metal ores below, with small contributions. This table shows that most environmentally relevant materials, e.g. Lead and light non-ferrous metals, are currently efficiently recovered and recycled, and therefore the resource efficiency of the automobile is already very high with regard to the environmental impact of materials use. From these results, it seems that a purely weight-based recovery target is a inadequate measure of the sustainability of the automobile resource use, because materials are not all equally important from an environmental perspective.

Table 8: Contributions of most important resources to total environmental impact according to EI 99

Substance	Contribution to EI (%)
Crude oil	46.49
Natural gas	3.39
Copper (in ore)	5.00 E-2
Coal	7.00 E-2
Lead (in ore)	1.00 E-2
Zinc (in ore)	8.00 E-3
Bauxite	4.00 E-3
Iron (in ore)	1.00 E-3

5 Conclusion and Recommendations

From examination of the results of the LCA of the average passenger vehicle in the Netherlands, the following conclusions and recommendations arise, according to the Eco-Indicator 99:

- Most of the impact – over 90% – originates in the use phase. So, future efforts for the reduction of the environmental impacts and increasing the sustainability of passenger vehicles must consider the reduction of the environmental impact of the use phase; nevertheless, effort must be put as well in the recovery of materials, in order to recover valuable materials and close the resource cycles;
- According to this eco-indicator, the largest contribution to the environmental impact is 'Fossil Fuels Depletion', followed by the emission of 'Respiratory Inorganic Substances' and 'Acidification/Eutrophication'. Other eco- indicator methods were used elsewhere to evaluate the environmental impact of passenger vehicles. Their results are consistent for all indicators, with small differences that can be attributed a different approach in the evaluation of the several methods: the combustion and depletion of fossil fuels with its consequences to the human health, the ecosystems and the resources are the largest environmental impact in the passenger vehicle's life cycle;
- Fossil fuels combustion, with emission of the resulting gasses and resource depletion are the dominant causes of environmental impact not only in the use phase, but in all life cycle phases as well, i.e., also during production, EOL and in the additional life cycles. Only for the 'Battery' life cycle the emission of 'Respiratory Inorganic Substances' has a larger contribution than fossil fuels depletion;
- The emissions to air that cause the highest impact are also related to the combustion of fossil fuels. The emission of CO_2 to air is the largest emission in amount, but its impact is only 6% of the total environmental impact, while NO_x emission is much lower, but responsible for 36% of the total environmental impact, thus being the second largest contributor to the eco-indicator value. It seems from these results that future legislation efforts to prevent air pollution should be based on the environmental impact of the emissions rather than plainly on their amounts;
- When analysing the resource losses, fossil fuel depletion is more important than metal ores depletion. This is due not only to the large use of fossil fuels during all phases of the vehicle life cycle, but also to the efficient recovery and recycling of the metals occurring in the ELV recycling in the Netherlands. Partial dismantling and recycling of vehicles seems to have therefore a very positive effect on its life cycle;

- Although there seems to be a growing awareness and concern on increasing the recyclability of vehicles, the use of fossil fuels is still the main environmental problem, and the ASR (Automotive Shredder Residue) is at this moment the greatest challenge with regard to recovery rate. It is an increasing amount of materials (23 wt.% in the ELV 1998 and about 32 wt.% in the ELV 2015), recycling is difficult and costly and thermal recovery is limited up to 15 wt.% in 1015. With the tendency to increase the use of lightweight materials, it will become more difficult in the future for ELVs to meet the EU recycling legislation targets. The results of this LCA should therefore not be considered separately from this fact, but can be taken into account in the joint efforts of the automotive industry and legislative institutions to increase the sustainability of passenger vehicles.
- Although the inventory for the average passenger vehicle cannot be exhaustive due to the limitations arising from defining an average passenger vehicle (average weights and compositions, use, etc...), the main results agree with those of previous studies. Therefore, the authors think that with this study a sound basis is set for the comparison of future vehicle design alternatives generated in the project.

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